

Comparison of the Josephson Voltage Standards of the INM and the BIPM

(part of the ongoing BIPM key comparison BIPM.EM-K10.b)

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Abstract. A comparison of the Josephson array voltage standards of the *Bureau International des Poids et Mesures* (BIPM) and the *Institutul National de Metrologie* (INM), Bucuresti, Romania, was carried out in June 2014 at the level of 10 V. For this exercise, options A and B of the BIPM.EM-K10.b comparison protocol were applied. Option B required the BIPM to provide a reference voltage for measurement by INM using its Josephson standard with its own measuring device. Option A required INM to provide a reference voltage with its Josephson voltage standard for measurement by the BIPM using a *analogue* nanovoltmeter and associated measurement loop. Since no sufficiently stable voltage could be achieved in this configuration, a *digital* detector was used. In all cases the BIPM array was kept floating from ground.

The final results were in good agreement within the combined relative standard uncertainty of 2.6 parts in 10^{10} for the nominal voltage of 10 V.

1. Introduction

Within the framework of CIPM MRA key comparisons, the BIPM performed a direct Josephson voltage standard (JVS) comparison with the INM, Romania, in June 2014.

The BIPM JVS was shipped to INM, Romania, where an on-site direct comparison was carried out from 18 June to 25 June 2014. The comparison followed the technical protocols for the options A and B of the BIPM.EM-K10 comparisons. The comparisons involved the BIPM measuring the voltage of the INM JVS using its measurement loop where a digital voltmeter was used as a

detector for option A and INM measured the voltage of the BIPM transportable JVS using its own measurement chain for option B.

For both protocol options, the BIPM array was kept floating from ground and was biased on the same Shapiro constant voltage step for each polarity, which was necessary to maintain stability during the time frame required for the data acquisition. For convenience, the BIPM array was biased at the same RF frequency with which INM operates its quantum voltage standard: $f=74.95$ GHz.

This article describes the technical details of the experiments carried out during the comparison.

2. Comparison equipment

2.1 The BIPM JVS

In this comparison the BIPM JVS comprised a cryoprobe with a *Hypres* 10 V SIS array (S/N: 2538F-3), the microwave equipment and the bias source for the array. The Gunn diode frequency was stabilized using an EIP 578B counter and an *ETL/Advantest* stabilizer [1]. An optical isolation amplifier was placed between the array and the oscilloscope to enable the array *I-V* characteristics to be visualized, while the array was kept floating from ground. During the measurements, the array was disconnected from this instrument. The measurements were carried out without monitoring the voltage across the BIPM JVS. The RF biasing frequency is always adjusted to minimize the theoretical voltage difference between the two JVS to zero and in most cases, the BIPM array can operate at the frequency of the participating laboratory.

The series resistance of the measurement leads was less than $3\ \Omega$ in total and the value of the thermal electromotive forces (EMFs) was found to be of the order of 600 nV to 700 nV. Their influence was eliminated by polarity reversal of the arrays. The leakage resistance between the measurement leads was greater than $5 \times 10^{11}\ \Omega$ for the BIPM JVS.

2.2 The INM JVS

The INM JVS is a fully automated system product of *Supracon* – Jena, Germany. The information presented here is taken from the User Manual of JVS, *Supracon*, September 2012.

The JVS cooled with a cryocooler consists of the following components:

1. Cryoprobe with the 10 V SIS JJ Array Chip (serial number:1792-C3) in the pulse tube cooler and the microwave electronics

2. JVS Electronics Unit
3. EIP Source Locking Microwave Counter, Phase Matrix 578 B
4. Keithley nanovoltmeter 2182A (nanovoltmeter)
5. Three channels polarity reversal switch
6. Sensors for temperature, pressure and humidity
7. Laptop with the suitable software
8. 2 kW Compressor Unit

Other information on the INM JVS:

- The microwave electronics consists of a Gunn oscillator with an integrated isolator, a directional coupler, a remote sensor, a voltage controlled attenuator and a power supply, assembled in the rack.
- The three channel computer-controlled polarity reversal switch, with very low thermal voltages (2 nV to 4 nV) and a resistance of the wiring of $1.5\ \Omega$, according to the manufacturer specifications.

3. Comparison procedures - Option B

The option B comparison took place before the option A comparison.

After the BIPM JVS was set up, the array of Josephson junctions was checked for trapped flux. The BIPM array was then successfully biased at the same frequency at which the INM operates its quantum voltage standard: $f = 74.95$ GHz. The BIPM JVS offers a large RF frequency band over which the quantum voltage is stable. This flexibility allows bringing some simplicity in the measurement process as if one of the two arrays jumps during the data acquisition, the effect is independent on the particular array and the software can deal easily with it. Furthermore, as it is possible to adjust the voltage difference between the two arrays to zero within one to three steps, this contributes to limit the impact of a change in the gain value of the nanovoltmeter during the measurement process.

During the time of the comparison, we didn't meet any strong instability of the voltages provided by the JVS especially in the best grounding configuration. Furthermore voltages appeared even more stable where both arrays were connected in series-opposition.

3.1 Measurement set-up

The measurement loop operated for the option B comparison is based on the INM *Supracon* JVS and embedded nanovoltmeter and software.

- 1- We started with the software option: "Zener calibration". The BIPM JVS was connected to one of the scanner channels (Channel A out of three choices available in total) which is part of the INM JVS system. In between the BIPM JVS and the scanner, a BIPM very-low-thermals switch was introduced in order to compensate the effect of the reversal of the INM scanner. Effectively, the polarity reversal must be performed at the level of the JVS (using the bias source) in order to cancel out the linear evolution of the thermal EMFs which exists between the array at liquid helium temperature and the top of the probe where the connections are made (room temperature). Therefore when the INM scanner applies a polarity reversal, the BIPM JVS is reversed two consecutive times: at the level of the array (bias source) and with the BIPM low thermal EMF switch to comply with the measurement process.

- 2- The software offers a second option called “direct comparison”. In this case, the INM scanner is not operated and the JVS voltage output to be compared (BIPM) is directly connected to the selected channel of the scanner. However, it was decided to keep the BIPM low thermal EMFs switch in order to be able to physically open the measurement setup.

The gain of the Keithley 2182A nanovoltmeter which measures the voltage difference was measured on a regular basis to correct the readings and also to derive an evaluation of the gain uncertainty.

During the measurement process, the BIPM bias source was adjusted manually to the same step after each polarity reversal. The voltage adjustment after a polarity reversal needed more than 30 seconds as the *Supracon* array needed the microwave power to be temporarily interrupted to reach a new quantum voltage.

3.2 Results of the option B

3.2.1 Preliminary measurements

The software allows a maximum number of eight individual measurement points in a single file and a preliminary series was performed within this configuration. The result, calculated as the mean value is: $(U_{\text{INM}} - U_{\text{BIPM}}) = 3.25 \text{ nV}$ with a standard deviation of the mean of 2.43 nV (Fig. 1). This result confirms that the INM SIS-junctions-based primary voltage standard offers a very satisfactory metrological reliability.

From the point of view of the grounding of the measurement loop, it was decided to leave both arrays floating from ground and to equalize the potentials of the chassis of the instrumentation together with the shield of the connection wires to the earth potential of the mains power distribution of the laboratory. This potential is by definition the reference potential of the INM JVS. After the preliminary measurements were carried out, more grounding configurations were investigated and are presented in the Appendix A of the report. However, the configuration described above was identified to be the best in terms of the lowest electrical noise as the standard deviation of a single data acquisition set (10 consecutive readings at NPLC=1) was at least twice lower than within any other grounding configuration. Surprisingly, there were no visible consequences on the dispersion of the results (measurement points *ie* voltage differences between the two standards computed from the sets of DVM readings).

However, the best grounding configuration was kept during the remaining period of the comparison as the stability of the voltages achieved on both standards was improved.

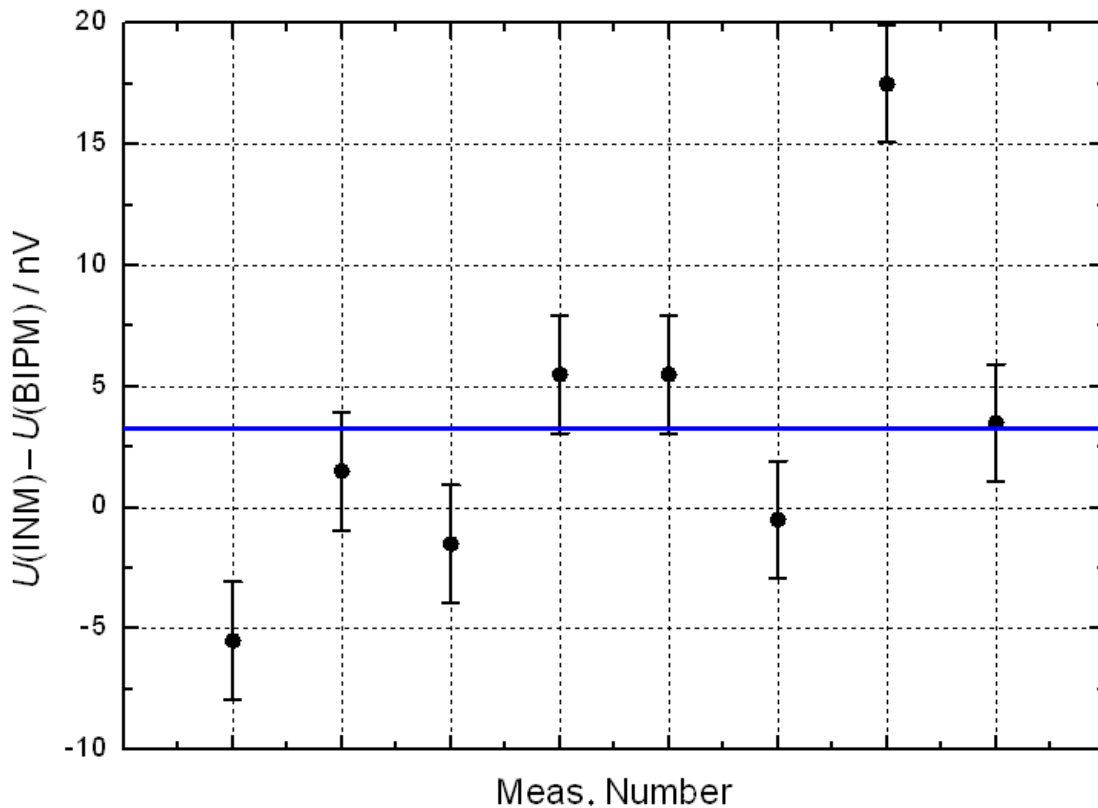


Fig. 1: Individual results obtained with the Option B comparison protocol at the 10 V level. The uncertainty bars represent the standard deviation of the mean of the complete series. The line slightly above zero represents the mean value of the 8 individual measurements (+3.25 nV).

3.2.2 Direct comparison configuration (INM software)

The INM JVS software offers an option of direct comparison where the polarity of the BIPM JVS is taken into account as the relay of the INM scanner only opens and close the circuit on the same contact (without reversal). Within this software option, if the noise level (internal consistency) is larger than a certain level fixed by the manufacturer and which can't be changed by the operator, the measurements are not taken into account by the software and the user is only informed to keep proceeding with the measurement process.

We could only carry out 11 complete measurements from 5 different measurement series. The mean value is: $(U_{\text{INM}} - U_{\text{BIPM}}) = 0.1 \text{ nV}$ with a standard deviation of the mean of 4.1 nV (Cf. Fig. 2).

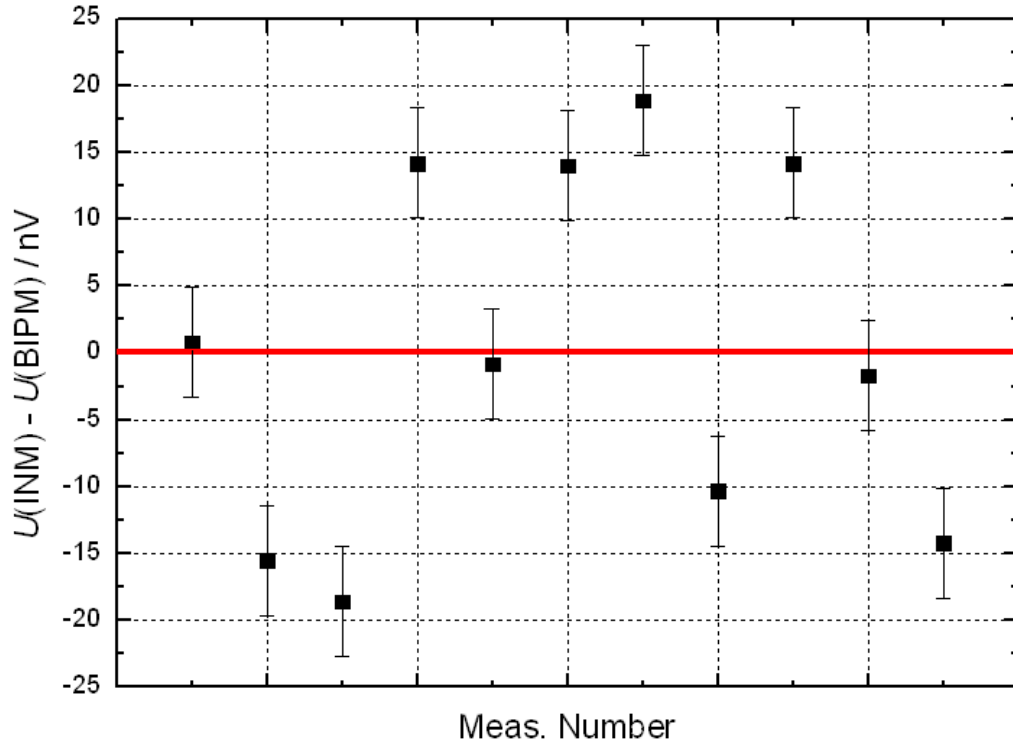


Fig. 2: Individual measurement points (black squares) obtained to calculate the result of the option B at the level of 10 V while using the “direct comparison mode” of INM software. The solid line represents the mean value and the uncertainty bars represent the experimental standard deviation of the mean of the 11 individual measurement points ($k=1$).

We note that even if the Type A uncertainty is expanded to the $k=2$ coverage factor, most of the points do not cover the dispersion of the series. We assume that the measuring process and related calculation process are not sufficiently known to take those results into account for the final result.

From the results presented in the previous paragraphs, we decided to switch to a new version of the software (ver. 2.3) which allows to connect the low potential side of the INM array to the reference potential. The aim was to investigate on a new possible grounding configuration of the measurement setup. The installation of the software was very much time consuming as we encountered several compatibility errors with the computer OS (Cf. Appendix A). Once we could perform some new measurements, it appeared that grounding the low side of the INM array brought too much instability in the measurement setup to perform an acceptable measurement.

3.2.3 Conclusion

The preliminary result which is the first one obtained when the comparison was started couldn't be improved despite we tried different software options and versions.

The result obtained from the option B comparison protocol is therefore also the preliminary one: $(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = 3.25 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{\text{BIPM}} = 2.43 \times 10^{-10}$.

4. Comparison procedures - Option A at the 10 V level

4.1 First series of measurements using a digital nanovoltmeter

In order to use an analog detector, both arrays need to remain on the quantized voltage step for at least one minute in each polarity. To investigate on the stability of the measurement setup within the option A configuration, we first inserted a digital voltmeter (HP34420A on its 10 mV range): if any of the two arrays jumps away from the selected step during the readings acquisition, the detector won't go on overload.

Furthermore, the *Supracon* software offers an arbitrary DC voltage synthesis within two optional intervals ($\pm 2 \mu\text{V}$ and $\pm 5 \text{ mV}$). Once the measured voltage exceeds the limits of the voltage settings, the software automatically readjusts the array parameters and the comparison mode is stopped.

The first result, obtained from 10 consecutive measurements points, gave:

$$(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = 4.5 \times 10^{-10} \text{ with a relative Type A uncertainty } u_A / U_{\text{BIPM}} = 9.32 \times 10^{-10}.$$

Once the gain of the 10 mV range of the BIPM HP34420A was calibrated several times, two consecutive series of 5 measurement points were carried out for which the mean value of the voltage difference was still of the order of 5 nV with an associated relative significant Type A uncertainty varying from 1×10^9 to 3×10^9 (Cf. Appendix A).

We then decided to reverse the polarity of the detector to see if the sign of the voltage difference between the two arrays would change. No impact on the measurements was identified.

We performed several series of 5 consecutive measurement points while changing the following parameters in the setup configuration:

- 1- Both laptops remained connected to their respective power supply;

- 2- Both laptops' power supplies were removed from their respective computers;
- 3- The reference potential was disconnected from all the chassis of the equipments, except for the INM JVS;
- 4- The analog filter of the nanovoltmeter was engaged.
- 5- The HP34420A nanovoltmeter was replaced by a Keithley 2182A.

None of those manipulations had an effect on the relative Type A uncertainty which was still of the order of 10 nV to 20 nV.

4.2 Second series of measurements using an analog detector EM-N11

From the previous measurements, the stability and electrical noise level (interferences between the two primary standards and corresponding grounding configuration) were found adequate to replace the digital nanovoltmeter with the BIPM analogue detector.

The voltages provided by both Josephson voltage standards could be easily adjusted on the same Shapiro voltage step while using the digital nanovoltmeter but surprisingly, the INM array lost its stability after the analogue detector was installed, probably as a consequence of its installation. Despite several attempts, we couldn't achieve a single measurement in this configuration.

Therefore the option A protocol could only be partially carried out because the use of the analog detector was not possible. The result of 20 measurements obtained with the digital voltmeter, described in section 4.1, (Cf. Fig.3) is: $(U_{\text{NIM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = 6.99 \times 10^{-10}$ with a relative experimental standard deviation of the mean of $u_A / U_{\text{BIPM}} = 11.29 \times 10^{-10}$.

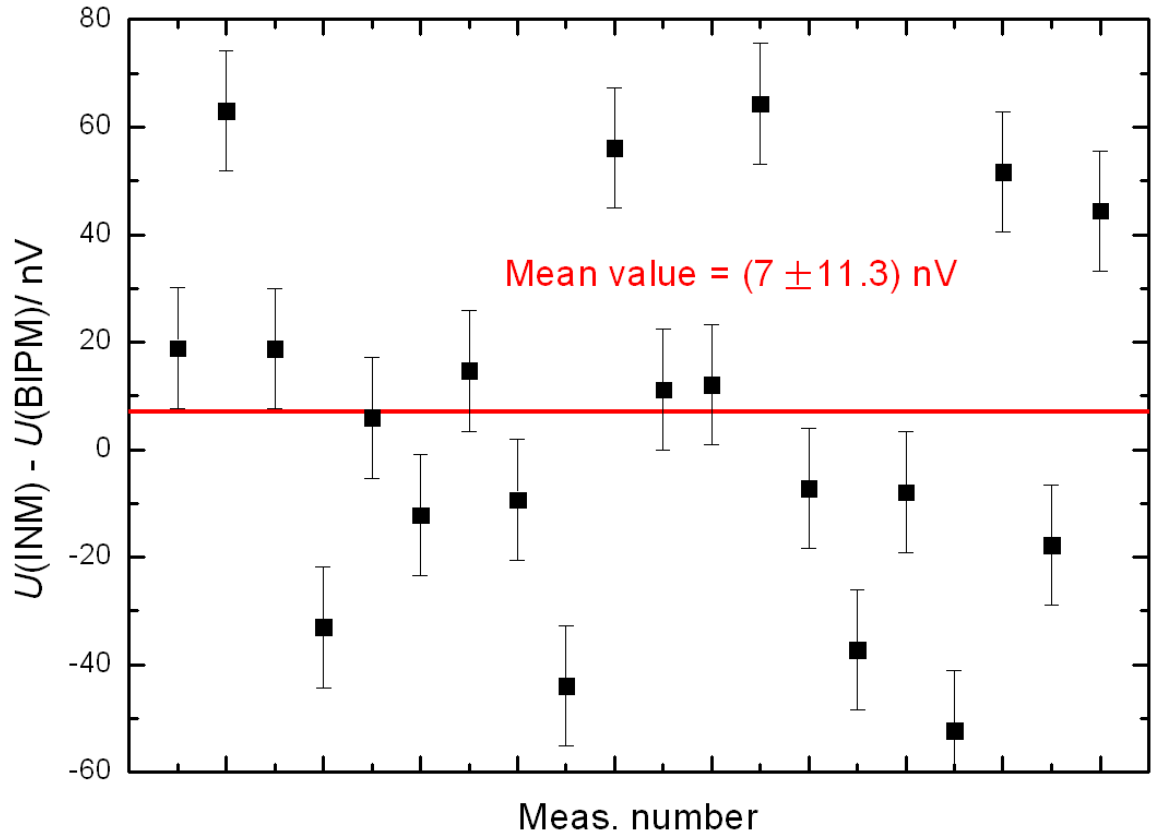


Fig. 3: Individual measurement points (black squares) obtained to calculate the **partial** result of the option A comparison scheme at the level of 10 V using a **digital** nanovoltmeter. The solid line represents the mean value and the uncertainty bars represent the experimental standard deviation of the mean of the 20 individual measurements.

5. Uncertainties and results

5.1. Type B uncertainty components (option B protocol)

The sources of Type B uncertainty (Table 1) are: the frequency accuracy of the BIPM and the INM Gunn diodes, the leakage currents, and the detector gain and linearity. Most of the effects of detector noise and frequency stability are already contained in the Type A uncertainty. The effect of residual thermal EMFs (*i.e* non-linear drift) and electromagnetic interferences are also contained in the Type A uncertainty of the measurements because both array polarities were reversed during the measurements. Uncertainty components related to RF power rectification and sloped Shapiro voltage steps are considered negligible because no such behaviour was observed.

	Type	Relative uncertainty	
		BIPM	INM
Frequency offset ^(A)	B	8.0×10^{-12}	13.3×10^{-12}
Leakage resistance ^(B)	B	3.3×10^{-12}	12.4×10^{-12}
Detector ^(C)	B		9.0×10^{-11}
Total (RSS)	B	1×10^{-11}	9.2×10^{-11}

Table 1: Estimated Type B relative standard uncertainty components (Option B).

^(A) As both systems referred to the same 10 MHz frequency reference, only a Type B uncertainty from the frequency measured by the EIP is included. The 10 MHz signal used as the frequency reference for the comparison was produced by the internal reference of the BIPM frequency counter EIP 578B.

The BIPM JVS has demonstrated on many occasions that the EIP-578B has a good frequency locking performance and that the accuracy of the frequency can reach 0.1 Hz [2]. However, in the particular case of using the internal EIP frequency reference, we consider a frequency offset of 1 Hz to which we apply a rectangular distribution as we couldn't check the frequency accuracy. The relative uncertainty for the offset of the frequency can be calculated from the formula: $u_f = (1/\sqrt{3}) \times (1/75) \times 10^{-9} = 8 \times 10^{-12}$.

^(B) If a rectangular statistical distribution is assumed then the relative uncertainty contribution of the leakage resistance R_L can be calculated as: $u_f = (1/\sqrt{3}) \times (r / R_L)$. For INM, the related variables were measured to $r = 2.15 \, \Omega$ and $R_L = 1 \times 10^{11} \, \Omega$. The isolation resistance value includes all the cables from the JVS to the DVM. For BIPM, those parameters are measured to $r = 3.65 \, \Omega$ and $R_L = 5 \times 10^{11} \, \Omega$.

^(C) For INM JVS, a Keithley 2182A served as the null detector, with the correction of (30 ± 0.3) ppm on its 10 mV range. The uncertainty on the gain has been obtained as the standard deviation of the mean of 5 measurements of the gain performed at different time during the comparison. As the voltage difference was adjusted with the maximum of 3 mV, when a normal distribution is assumed, the relative standard uncertainty on the detector can be calculated as $u_d = 9.0 \times 10^{-11}$.

5.2 Result at 10 V (option B)

The result obtained following option B of the protocol, is expressed as the relative difference between the values attributed to the 10 V BIPM JVS (U_{BIPM}) by the INM JVS measurement set-up (U_{INM}) and by the BIPM:

$$(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = 3.25 \times 10^{-10} \quad \text{and} \quad u_c / U_{\text{BIPM}} = 2.60 \times 10^{-10}$$

where u_c is the total combined standard uncertainty and the relative Type A is

$$u_A / U_{\text{BIPM}} = 2.43 \times 10^{-10}.$$

This result fully supports the CMCs (Calibration and Measurement Capabilities) of the INM.

6. Conclusion

The comparison was carried out in the INM Electricity Laboratories where the environmental conditions allowed to meet good conditions for the stability of the quantum voltages. The INM Josephson Voltage Standard is a commercial system based on a cryocooler cooling equipment. The cryo-pump was installed in a room next to the laboratory. The electrical noise environment was found very satisfactory as in particular, the voltages provided by the two arrays were very stable during the time allotted to the comparison. However, despite a lot of efforts, we couldn't improve the preliminary result obtained at the beginning of the exercise. When applying the option A of the protocol, we could control more degrees of freedom in the measurement setup as the BIPM transportable JVS offers flexibility in the adjustment parameters of the array, the setup and its associated software, but we couldn't lower the relative Type A uncertainty to below 1×10^{-9} . We couldn't clearly identify which component of the measurement loop was responsible for such a level of electrical noise, however we suspect a possible issue with the residual contact voltages of the scanner, which were observed to be between 10 nV to 20 nV for the three positions available.

The final result fully supports INM CMCs in the field of DC voltage Metrology.

References

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- [2] Djordjevic S. *et al.*, Direct comparison between a programmable and a conventional Josephson voltage standard at the level of 10 V, 2008 *Metrologia* **45**, 429.

[3] Solve S., R.Chayramy, M. Stock, J. Nicolas and A. van Teemsche , Comparison of the Josephson Voltage Standards of the SMD and the BIPM (part of the ongoing BIPM key comparison BIPM.EM-K10.b), *Metrologia*, 2010, **47**, *Tech. Suppl.*, 10104.

[4] Solve S., R.Chayramy, M. Stock, Yi-hua Tang and J.E. Sims , Comparison of the Josephson Voltage Standards of the NIST and the BIPM (part of the ongoing BIPM key comparison BIPM.EM-K10.b), *Metrologia*, 2009, **46**, *Tech. Suppl.*, 01010.

DISCLAIMER

Certain commercial equipment, instruments or materials are identified in this paper in order to adequately specify the environmental and experimental procedures. Such identification does not imply recommendation or endorsement by the BIPM or INM, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Appendix A

This appendix describes the measurements performed in chronological order.

18 June 2014:

The electromagnetic compatibility conditions were found excellent so that the BIPM JVS was assembled and tested without encountering any difficulties. The BIPM JVS equipment was powered from the same mains plug as the INM JVS equipment. Despite the fact that the laboratory is equipped with a dedicated earth connection line, we never used it to avoid ground loops with the mains power earth reference. The frequency of the BIPM RF signal was adjusted to that of the INM ($f = 74.95$ GHz) and the voltage of each array remained stable while the measurement loop remained closed with the two arrays connected in series opposition. The thermal EMFs in the circuit were measured to be of the order of 600 nV to 700 nV.

The preliminary result was achieved using the *Supracon* software dedicated to the calibration of secondary standards and where the BIPM JVS was playing this role.

The shielding cable of the INM scanner channel is referred to the earth potential and this reference potential was not connected to the instrumentation chassis. The relative standard deviation of the 20 nanovoltmeter readings (measurement set in one polarity of the arrays) was of the order of 110 nV – 120 nV.

For the following measurements, the reference potential was brought to the BIPM probe and Dewar through the shielding of the connection boxes. The shielding of the BIPM biasing cable is cut in such a way that there's no ground loop with the chassis of the biasing source which is powered from the mains. Within this grounding configuration, the relative standard deviation of a set of readings was relatively decreased to 50 nV– 60 nV. However, this noise reduction effect in the measurement loop didn't bring any improvement in the corresponding results (Cf. Fig. A1).

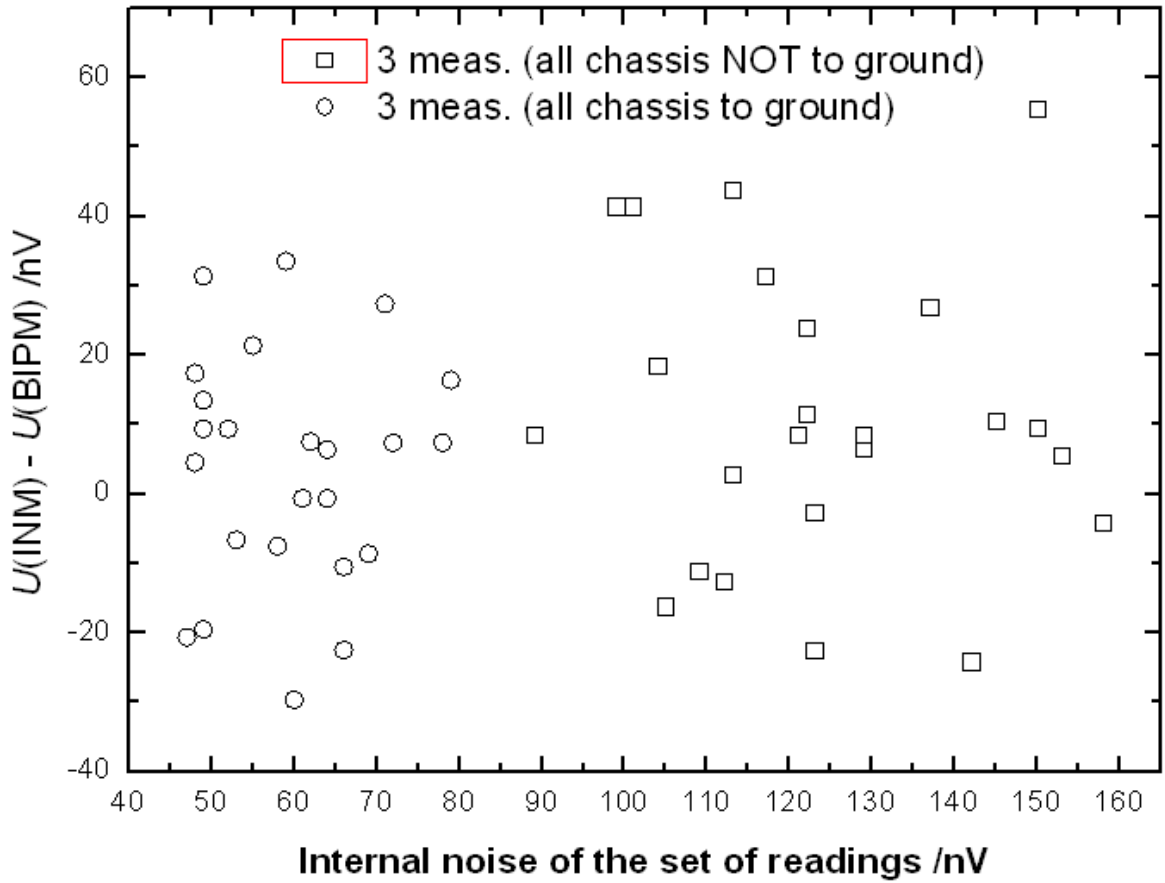


Fig. A1: Voltage difference between the two JVS as a function of the amplitude of the noise in the set of readings (internal consistency): black circles when the equipment chassis of the measurement loop are connected to ground, black squares when the equipment chassis are connected together but NOT to the ground.

In the version of the *Supracon* software, we use (2.2), the configuration file doesn't exhibit the gain correction factor which is taken into account to correct the nanovoltmeter readings. A spreadsheet was then set up to calculate the results from the raw data where the detector gain could clearly be taken into account.

We decided to change the nanovoltmeter to see if this parameter had an impact on the results. We couldn't monitor any related effect.

Although there was no indication of a ground loop through the outer part of the 10 MHz BNC reference cable, we decided to install an isolation transformer on the 10 MHz reference line

provided by the INM Time Department. However we couldn't install the BIPM GPIB bus isolator as the nanovoltmeter couldn't receive the command line anymore.

The preliminary comparison result, using a digital nanovoltmeter was achieved on that day from 8 individual measurements to: $(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = 3.25 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{\text{BIPM}} = 2.43 \times 10^{-10}$.

19 June 2014:

We started the day with the calibration of the gain of the 10 mV and 10 V ranges of the detector. The 10 mV correction is of the order of 50 ppm and variation of 10 ppm could be monitored during the day. As pointed out in a previous comparison [3], the nanovoltmeter sits on the frequency counter in the measurement rack. During its phase locking regime, this equipment generates a significant amount of heat that will affect the nanovoltmeter gain. To avoid any significant impact on the comparison results, the gain was calibrated on a regular basis with the dedicated menu of the software.

We tried to carry out a measurement with the low side of the BIPM array connected to ground but the noise level was so high that we couldn't achieve a stable voltage.

We therefore switched back to the configuration where both arrays are floating and we tried different grounding configurations:

- 1- The reference potential was brought from the BIPM biasing source chassis to the INM scanner but the shield of the connection wire was left opened. A second series was carried out with channel B and a third one with channel C. The results are presented on figure A2.
- 2- The reference potential was always the mains Earth potential and couldn't be changed because of the INM equipment arrangement. We would have needed an isolation transformer to use the dedicated metrological Earth potential of the laboratory.
- 3- A third and last configuration was tested where the reference potential was brought from the BIPM biasing source chassis up to the INM equipment but interrupted at the level of the shielding of the cable of the scanner channel. The internal consistency jumped back to a relative level of 20 nV but the external consistency remained at the same level of 10 nV to 20 nV.

At this point, we decided to investigate on the residual thermal electromotive forces of the scanner. A special part of the software is dedicated to that type of measurement. A good quality short circuit was installed on each of the 3 outputs and we found repeatable

measurements of 10 nV, 15 nV and 19 nV for channels A, B and C respectively. Those results are higher as the ones specified by the manufacturer (5 nV).

We then decided to run the software dedicated to direct JVS comparison. Only a few measurements could be recorded because of a fixed parameter in the software: If the noise level (internal consistency) is larger than a certain value implemented by the manufacturer and unknown to the user, the measurements are not taken into account and the user is only requested to continue with the measurement process.

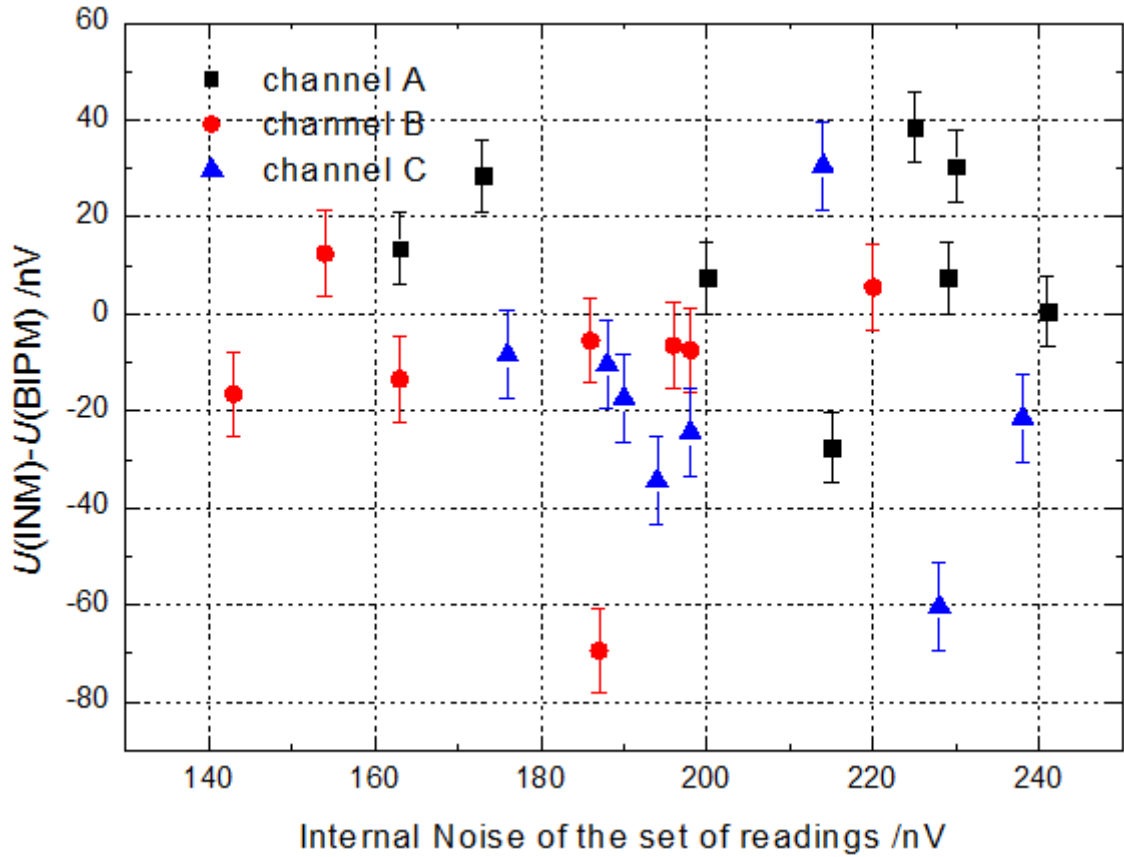


Fig. A2: Voltage difference between the two JVS as a function of the amplitude of the noise in the set of readings (internal consistency): effect of the different channels of the INM scanner (black squares-channel A, red disks-channel B, blue triangle-channel C). The uncertainty bars represent the Type A uncertainty of the series.

At this point, we decided to install the new version of *Supracon* software (Ver 2.3), this update allows to ground the low side of the array in the Zener calibration menu of in the direct comparison mode. At BIPM, we are used to perform the two kinds of measurement methods when we perform internal Josephson comparisons. If a significant difference is observed, this would indicate a weak grounding condition of the measurement setup or an important leakage current.

20 June 2014:

The installation of the software continued all the day long as we encountered several issues:

- 1- The communication between the software and the instrumentation of the INM JVS is provided by a USB-GPIB IEEE 488 connection device from Keithley. The software is written under National Instrument Labview environment and we faced issues of compatibility between the software and communication hardware. We tried different solutions as re-installing the drivers (NI-488 and Keithley USB-GPIB plug) in different ways but couldn't make those devices to operate properly.
- 2- The new version of the software was asking for a dynamic library file that was missing. It appears that this file should exist only on a PC equipped with Windows 8. Surprisingly, the INM laptop was working under Windows 7 environment.
- 3- As the software version 2.3 installation CD appeared defective, we tried to restore the *Supracon* software to an anterior stable version (ver 2.2). This operation was unsuccessful.
- 4- We lent the BIPM NI-USB-GPIB interface to INM. This had the effect to resolve all the software issues and confirmed that the main issue was related to compatibility between the devices and the software. However, as the BIPM equipment also needed to operate this interface for the future option A comparison, we had to go through equivalent compatibility issues with an Agilent USB-GPIB interface we borrowed from INM. We fortunately managed to make it operational!

At the end of the day, we managed to carry out a direct comparison using version 2.3 of the software with three consecutive points. Between the 19th and the 20th of June, a total of 11 points could be achieved using the direct comparison mode. The corresponding result obtained is the following: $(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = -0.09 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{\text{BIPM}} = 4.1 \times 10^{-10}$.

21 June 2014:

We decided to run the direct comparison mode of the new software version to try to improve the preliminary measurements. The selected grounding configuration was the one where the lower standard deviation of the readings was obtained: the reference potential (INM instruments earth potential) is brought to the BIPM equipment and the dewar through the shielding of the connecting leads.

The 10 mV range gain of the INM Keithley 2182A nanovoltmeter was measured 5 times consecutively with a pause of 5 min to 10 min between each measurement. The aim is to use the dispersion on the detector gain from these measurements together with the largest voltage measured with the nanovoltmeter to derive a corresponding Type B uncertainty.

The direct comparison mode was then started with the same frequency for both JVS: 74.95 GHz. We didn't manage to get a single measurement result despite several attempts because of the unknown and non-adjustable noise level threshold imposed by the software.

As we couldn't go any further with the option B comparison, we decided to switch to the option A comparison protocol.

The *Supracon* software offers an arbitrary DC voltage synthesis within two optional intervals ($\pm 2 \mu\text{V}$ and $\pm 5 \text{ mV}$). Once the measured voltage exceeds the limits of the voltage settings, the software automatically readjusts the array parameters. We noticed that the array voltage was not stable for more than a few seconds (typically 5 s to 7 s) while on its own. It appeared that the connection of the INM array in series opposition with the BIPM standard improved its stability. We started the comparison using a digital voltmeter (HP34420A on its 10 mV range) and the first series of 10 measurements points gave: $(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = 4.5 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{\text{BIPM}} = 9.32 \times 10^{-10}$.

During the lunch break, we run a frequency scan on the INM array in order to detect any other RF frequencies than the default one (74.950 GHz) to be successfully operated. The software detected $f=74.97 \text{ GHz}$ to which the array offered the best margins but all the frequencies comprised between $f=74.95 \text{ GHz}$ and $f=74.99 \text{ GHz}$ offer a continuous frequency interval where the array responds with stable voltages. The following frequencies also offered nice responses from the array: $f=74.9 \text{ GHz}$, $f=75.09 \text{ GHz}$ and $f=75.1 \text{ GHz}$.

The gain of the 10 mV range of the BIPM HP34420A was calibrated several times and two consecutive series of 5 measurement points were carried out and gave the following results respectively:

$(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = -3.46 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{\text{BIPM}} = 31 \times 10^{-10}$
and $(U_{\text{INM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = -11.04 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{\text{BIPM}} = 13 \times 10^{-10}$.

It must be pointed out that the nanovoltmeter readings acquisition is performed without any electrical activity on the IEEE bus. The data are recorded into the internal memory of the device

before being transferred to the computer. In addition the two first readings are automatically discarded from the set of readings. In order to avoid any ground loop and to avoid the radiated electrical noise from its power supply, the computer is powered from its internal battery.

We tried to perform a series with the nanovoltmeter analog filter activated but the noise level was considerably increased and the acquisition was aborted.

23 June 2014:

The battery of the INM laptop which runs the *Supracon* software is out of order and therefore its power supply needs to be constantly connected to the mains. In order to investigate on the possible noise contribution of the power supply, we decided to install the *Supracon* software on a second laptop, operated on batteries and run a series acquisition.

We performed two series of measurements with the laptop powered from batteries for which the relative Type A uncertainty was still of the order of 2×10^{-8} and the relative mean values of the voltage difference between the two arrays were $m = -12.9 \times 10^{-10}$ and $m = -8.7 \times 10^{-10}$ respectively. We then decided to reverse the polarity of the detector to see if the sign of the voltage difference between the two arrays would change while measuring ($U_{\text{BIPM}} - U_{\text{INM}}$). No metrological impact was found.

We performed several series of 5 consecutive measurement points while changing the following parameters in the setup configuration:

- 6- Both laptops remained connected to their respective power supply;
- 7- Both laptops' power supplies were removed from their respective computers;
- 8- The reference potential was removed from all the chassis of the equipments, except for the INM JVS;
- 9- The analog filter of the nanovoltmeter was engaged.

None of those manipulations had an effect on the Type A uncertainty which was still of the order of 10 nV.

We decided to change the HP34420A nanovoltmeter to a Keithley 2182A nanovoltmeter as we wanted to investigate on the assumption that the nanovoltmeter was responsible for the high noise level on the measurements.

We carried out several consecutive calibrations of the 10 mV gain. To achieve this, we had to trick the software and calibrate the Keithley nanovoltmeter as if it was the INM internal JVS one. The software menu "external nanovoltmeter calibration" was not working any longer.

24 June 2014:

The comparison setup was set back to the best grounding configuration where the voltages provided by both arrays were always very stable. Different series of 5 measurement points were performed but we couldn't find a relative Type A uncertainty lower than 15×10^{-8} which is still pretty significant.

The Keithley 2182A was replaced with an equivalent device but no improvement in the measurements could be observed. As both voltages were very stable and could be adjusted on the same Shapiro voltage step, we decided to try to install the BIPM EM N11 analog nanovoltmeter to measure the voltage difference between the arrays. Surprisingly, the INM array lost its stability and despite several attempts, we couldn't achieve a single measurement within this configuration.

25 June 2014:

We decided to move back to the option B comparison protocol again for the remaining few hours dedicated to the exercise.

- 1- The direct comparison mode offered by the software was unsuccessful;
- 2- We tried again the Zener measurement mode from which the preliminary measurements had been obtained and not improved since.

Two series of measurement were performed with a relative Type A uncertainty respectively equal to 9×10^{-10} nV and 4×10^{-10} nV.

The remaining time was dedicated to the measurement of the line resistance of the measurement leads of the INM JVS. As the array couldn't be removed, we used the method operated at NIST in 2009 [4]:

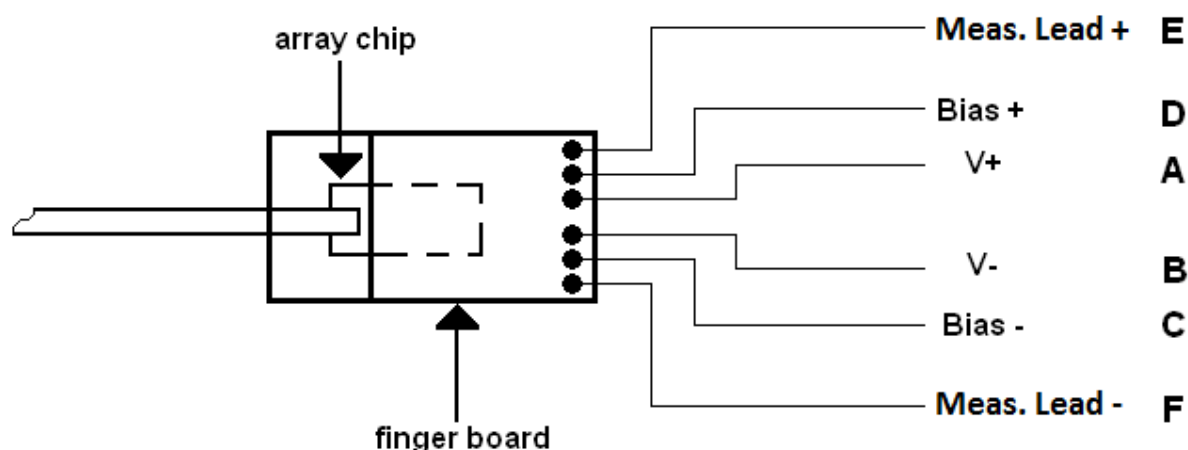


Fig. A2. Details on the connection of the leads (potential, bias and measurement) on the finger board.

The measurements are presented in the following table (Cf. **Table A1**):

Resistance Meas.	INM JVS (Ω)	BIPM JVS (Ω)
AE; BF	2.0; 2.1	2.8; 2.7
DE; FC	2.1; 2.2	2.9; 2.9
AD; CB	2.0; 2.1	2.0; 2.0
ADE*; BCF*	3.2; 3.35	3.85; 3.8

Table A1. Results of the measurements of the resistance of the biasing and measurement leads while connected to the array at 4 K.

* Those components represent the sum of the resistance of the three leads (i.e. terminals ADE and BCF are shorted).

Note: a residual resistance of 0.1 ohm (multimeter offset error) was subtracted from all the measurements.

The resistance of the measurement leads is deduced from the formula: $r_B = E + F$;

$$r_B (\text{INM}) = 2.15 \, \Omega$$

$$r_B (\text{BIPM}) = 3.65 \, \Omega$$

The isolation resistance between the two measurement leads is taken from the Manufacturer certificate for which a degradation factor of 1.5 is applied.

The corresponding leakage resistance voltage error on the 10 V output of the INM JVS is:
 $e = 10 \, \text{V} \times 2.15 / (100 \times 10^9) = 0.225 \, \text{nV}$.

The voltage error of the BIPM system is: $e = 10 \, \text{V} \times 3.65 / (500 \times 10^9) = 0.1 \, \text{nV}$.